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Observation of an enhanced Aharonov–Bohm effect

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Abstract

A new measurement scheme to investigate the Aharonov–Bohm (AB) effect is proposed. We have found that the AB amplitude relative to the total signal becomes much more enhanced in a non-local four-terminal configuration than that obtained in the conventional four-terminal configuration and the AB phase can be continuously controlled electrostatically. It is shown that the Landauer–Büttiker formula explains these results. What is more important, the coherence of electron measured in the non-local setup is found to survive at higher temperature than that in the conventional one. The present result indicates that decoherence is affected by way of measurement and poses an important question on the mechanism of quantum decoherence.
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1. Introduction

Mesoscopic physics is intimately linked with measurement process. As the Landauer–Büttiker (LB) formula expresses [1], transport properties of a mesoscopic-sized sample can be interpreted only after taking account of the role played by the probe leads. This makes an essential distinction between mesoscopic and macroscopic samples. Manifestation of ballistic and coherent transport has been revealed by early 1990s in such phenomena as quenching of Hall effect, bend resistance and so on, and they have been well explained on the basis of the LB formula [2].

In this work, we study the ballistic Aharonov–Bohm (AB) effect in a mesoscopic ring fabricated from GaAs/AlGaAs two-dimensional electron gas system (2DEG). Previous studies on the AB effect have been conducted almost exclusively in two-terminal or conventional four-terminal setup, where both the voltage-probe pair and the current-probe pair are placed across the ring. Here, we have adopted a non-local measurement scheme and investigated the dependence on the probe configuration. Quite unexpectedly, we have found that electron decoherence is deeply affected by the probe configuration.

2. Experiment

We prepared a AB ring as shown in Fig. 1(a) by wet-etching a 2DEG at an AlGaAs/GaAs heterostructure with mobility 9×10^5 cm^2/V s and sheet carrier density 3.8×10^{11} cm^{-2}. The electron mean free path ~8 μm is larger enough than the length of one arm of the ring $L \sim 2$ μm, ensuring that the motion of electrons in the ring is quasi-ballistic. The Au/Ti metallic gates of width ~100 nm were deposited on the ring to control the AB phase and one specific gate marked 'G' was used in this study. The fabricated device allowed us two types of measurement. One was a conventional four-terminal measurement: electric current I_{14} was applied between the terminal 1 and 4, and then the voltage V_{23} between 2 and 3 was measured as shown in Fig. 1(b), giving the resistance $R_{14,23}$. Another setup shown in Fig. 1(c) is referred to as a non-local measurement setup henceforth, yielding the signal $R_{12,43}$ (current: $1 \rightarrow 2$, voltage: $4 \rightarrow 3$). Two samples (#1 and #2) with almost same geometry were measured, yielding essentially the same results.

3. Results and discussions

In the upper part of Fig. 2(a), we show the conventional resistance $R_{14,23}$ obtained at 30 mK. The AB oscillation is superposed on the magnetoresistance coming from the conductance channels other than those that encircle the

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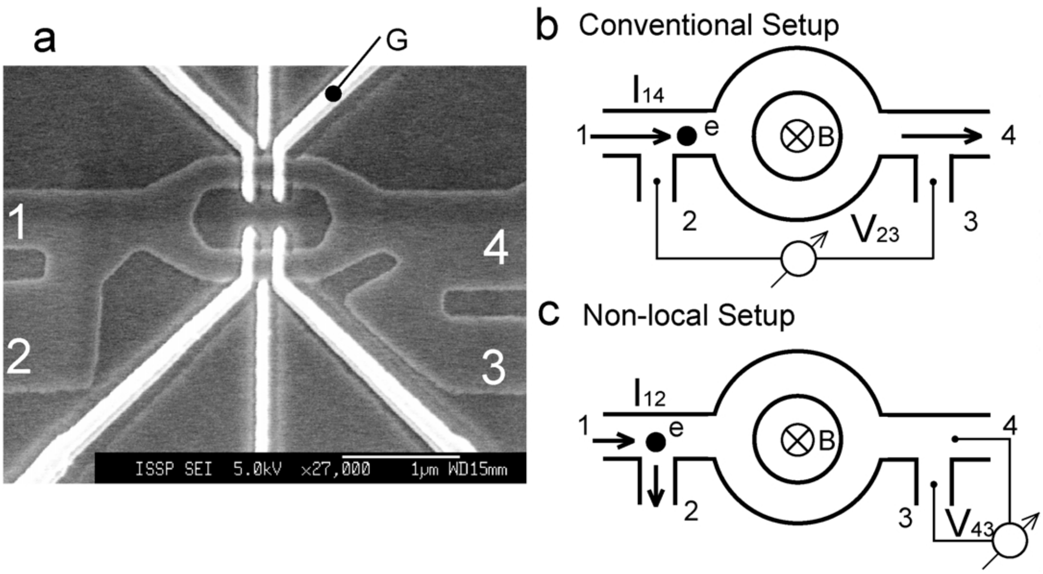

Fig. 1. (a) Scanning electron micrograph of the AB ring. One specific Au/Ti metallic gate marked as 'G' was used in this study. (b) The conventional four-terminal setup (current: $1 \rightarrow 4$, voltage: $2 \rightarrow 3$). (c) The non-local four-terminal setup (current: $1 \rightarrow 2$, voltage: $4 \rightarrow 3$). All the measurements were performed between 30 mK and 4.2 K using a dilution refrigerator. The standard lock-in techniques were used with typically $I_{14} = 3$ nA and $I_{12} = 15$ nA for the conventional and non-local setup, respectively, which were carefully checked to be sufficiently small to be free from any heating effect. To minimize the difference due to extrinsic effects and instrumental noise, exactly the same instrumental setup was used for both measurements.

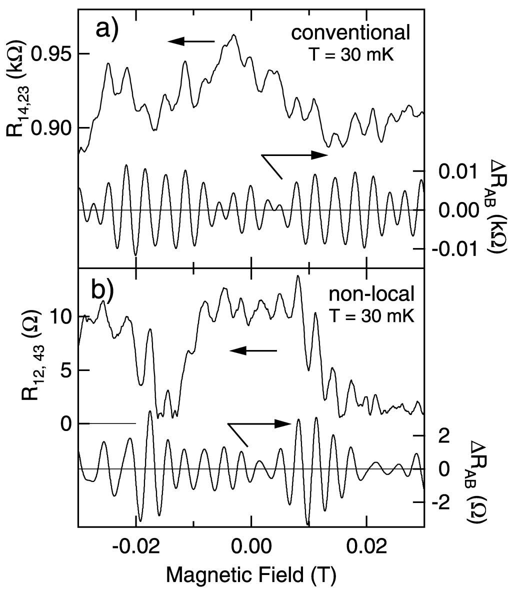

Fig. 2. (a) Typical AB oscillation obtained in the conventional setup. (Bottom) The AB component ΔR_{AB} digitally extracted from $R_{14,23}$ by means of the Fourier analysis. (b) The corresponding data obtained in the non-local setup.

ring. The oscillation period is $\Delta B_{AB} = 3.1 \pm 0.5$ mT, which agrees with the one expected from the ring dimension. The lower part of Fig. 2(a) shows the AB component (ΔR_{AB}) extracted from $R_{14,23}$ through fast Fourier transform (FFT), whose amplitude is about 2% of the total resistance of the ring ~ 1 kΩ. Fig. 2(b) represents the corresponding $R_{12,43}$ and ΔR_{AB} obtained in the non-local setup. The AB signal relative to the total resistance is quite enhanced that it averages up to 20% of the total signal with its maximum $\sim$75% at $B \sim -0.017$ T. This AB amplitude is the largest among all the AB experiments ever known. Indeed, the AB ratio reported to date is less than 0.1% for diffusive samples and usually a few percent, at most 25%, of the total resistance even for ballistic devices [3].

We show that the above is a unique property of the non-local measurement derived from the LB formula. According to the LB formula [1], $R_{14,23} = (h/2e^2)(T_{21}T_{34} - T_{24}T_{31})/D$ and $R_{12,23} = (h/2e^2)(T_{41}T_{32} - T_{42}T_{31})/D$, where T_{ij} (≥ 0) is a transmission coefficient from terminal i to j ($i,j = 1,\ldots,4$, $i \neq j$) summed over the relevant conductive channels and a denominator D is a function including all the T_{ij}s. To include the AB effect, T_{ij} in a single conductive channel case can be expressed as $T_{ij} = \alpha_{ij} + \beta_{ij}\cos(2\pi\Phi/\Phi_0 + \Delta)$, where α_{ij} and β_{ij} are functions of B, temperature T, and electron energy. Here, Φ_0 is a flux quantum, and Φ is magnetic flux surrounded by the electron path. Δ represents a geometrical phase difference that an electron wave acquires along its path around the ring.

When there exist multiple conductive channels, T_{ij} should

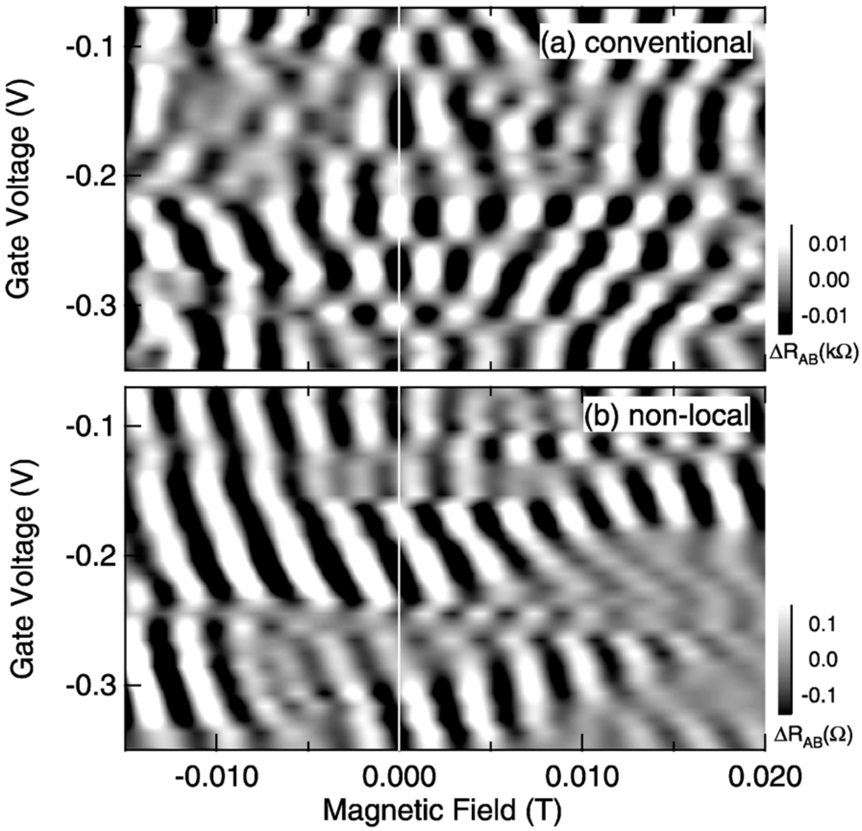

Fig. 3. Density plots of the AB phase variation as a function of V_G observed in: (a) conventional and (b) non-local configuration. The white and black parts correspond to the maximum and minimum of the AB oscillation, respectively.

be the sum over the incoming and outgoing channels. If we consider a most simplified case by assuming that $T_{12} = T_{21} = T_{34} = T_{43} = T_0$, $T_{14} = T_{41} = T_{23} = T_{32} = T_1$, $T_{13} = T_{31} = T_{24} = T_{42} = T_2$, and $T_0 \gg T_1, T_2$, the LB formula gives $R_{14,23} \sim (h/4e^2)/(T_1 + T_2)$ and $R_{12,23} \sim (h/4e^2)/(T_1 + T_2)/T_0^2$. Presupposing that $T_i = A_i + B_i \cos(2\pi\Phi/\Phi_0)$ $(i = 1, 2)$ where A_i $(\geq|B_i|)$ and B_i are independent of magnetic field, the non-local signal $R_{12,43}$ extracts the AB component more effectively than the conventional $R_{14,23}$, resulting in the observed very large AB amplitude. Intuitively, in the conventional setup only a symmetrical part as to the magnetic flux contributes to the AB signal because the transmission coefficients bypassing the ring such as T_{12} and T_{43} are quite large in our geometry. On the other hand, the non-local signal is geometrically very small in the absence of the flux and hence the AB effect prominently appears as a deviation from this small signal. The above argument is fully supported by numerical simulation with realistic combinations of T_{ij}s.

Next, we focus on the control of the AB phase. The gray scale plots in Fig. 3(a) and (b) represent the AB oscillation obtained by varying the voltage (V_G) of the gate 'G' in the conventional and non-local setups, respectively. The variation of V_G affects the carrier density of the 2DEG underneath and hence the Fermi wave length electrostatically, yielding a continuous change of Δ. As shown in Fig. 3(a), however, the AB phase in the conventional setup is symmetric with respect to $B = 0$. As already reported [1,4,5], due to Onsager's reciprocal theorem, such a behavior is characteristic of the conventional four-terminal measurement which is effectively 'two-terminal', where the current and voltage terminals located at each side of the ring are common. On the other hand, the non-local result in Fig. 3(b) shows that the AB phase varies continuously as a function of B. This is not against the reciprocal theorem but can be explained by the LB formula for this probe configuration [1,5]. Indeed, we confirmed $R_{12,43}(B) = R_{43,12}(-B)$ being consistent with Onsager's theorem. Thus, by using the non-local four-terminal configuration, the AB phase can be controlled continuously unlike the conventional setup.

So far, we have seen that the non-local measurement is very unlike the conventional one, while the difference is well within the LB framework. However, we have found that there exists an essential difference between the two. In Fig. 4, we plot the temperature dependence of the FFT intensity of the AB component derived from $R_{14,23}$ and $R_{12,43}$. Each of the misnormalized to the FFT intensity at 30 mK, which is justified as the gross resistances except the AB

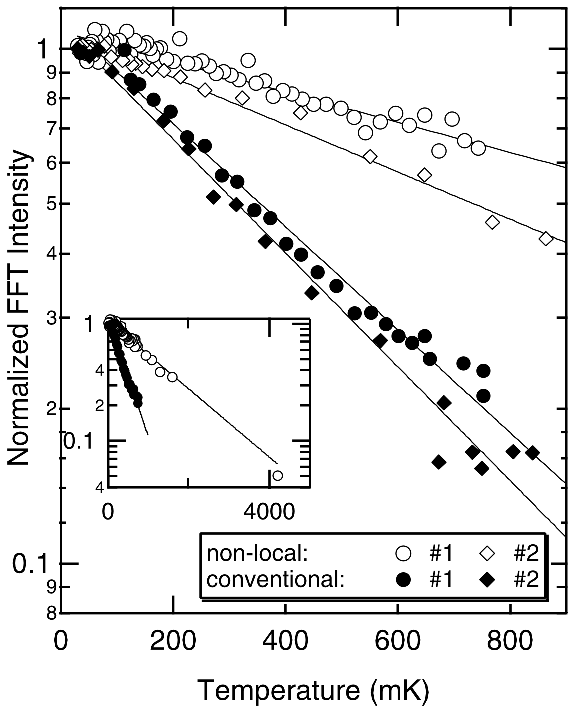

Fig. 4. Temperature dependence of the FFT intensity of the AB amplitude for the two types of measurement for the two samples (#1 and #2). The solid lines are fitted to the exponential decay function of temperature. The inset shows the result up to 4.2 K for the sample #1.

component are only slightly dependent on temperatures. Remarkably, the AB oscillation in the non-local setup is less dependent on temperature than that conventionally obtained. The data can be fitted to $\exp(-aT)$ with a as a fitting parameter. We obtained $a = 0.72$ and $1.0\ \mathrm{K}^{-1}$ for the non-local results while $a = 2.3$ and $2.5\ \mathrm{K}^{-1}$ for the conventional ones.

There are two main factors that can cause decrease of the AB amplitude with temperature. One is the thermal broadening of the electron wave packets. The other is the decoherence which contributes as $\beta_{ij} \propto \exp(-\tau_L/\tau_\phi(T))$ where τ_ϕ is a phase-coherence time and $\tau_L = L/v_\mathrm{f}$ (v_f: Fermi velocity). Since these effects are presumed to be included commonly in all the T_{ij}s, the temperature dependence of the AB amplitude should be the same regardless of the probe configuration as long as the same T_{ij}s in the LB formula are adopted in both measurements. Because the thermal averaging in the ballistic regime is deduced to occur in the time scale of $\tau_\mathrm{th} \sim \hbar/k_\mathrm{B}T$, τ_ϕ^{-1} is replaced by $\tau_\phi^{-1} + \tau_\mathrm{th}^{-1}$ and this τ_th would contribute to the AB degradation as $\exp(-bT)$ where $b \sim 1\ \mathrm{K}^{-1}$. Our observation, therefore, indicates that $\tau_\phi \propto T^{-1}$ with very different coefficients between both setups. Judging from this temperature dependence and the fact that the AB effect is observable even at 4.2 K in the non-local setup, we are lead to a conclusion that the coherence survives at higher temperature in the non-local setup than in the conventional setup.

Recently, several studies on the decoherence in the ballistic AB ring were reported. While Cassé et al. [6] explained the temperature dependence of the AB amplitude as due to the thermal averaging, Hansen et al. [7] showed that the thermal averaging is not enough to explain the AB degradation and $\tau_\phi \propto T^{-1}$, being consistent with our observation. Theoretically, Seelig and Büttiker [8] proposed that $\tau_\phi \propto T^{-1}$ due to the charge fluctuations caused by a nearby capacitor. Here, we propose that the observed configuration-dependent decoherence is due to the difference of the current path in the conventional and non-local setups. In the former setup, the momentum of the electron is almost conserved in traversing the ring from the terminal 1 to 4 since the motion of an electron is quasi-ballistic. In the latter setup, however, the momenta of the electron incoming from 1 and that outgoing from 2 are opposite in direction. Possibly, it gives rise to the suppression of charge fluctuation in the ring, and hence the coherence of electron might be preserved in the non-local setup. Decoherence may be caused in connection with a metallic gate [8]. It is added here that our observation of $\tau_\phi \propto T^{-1}$ gives an experimental evidence indicating that the claim for existence of intrinsic decoherence is disputable [9–12].

4. Conclusion

In a non-local four-terminal measurement of the AB experiment, the AB amplitude relative to the total signal becomes enhanced and the AB phase can be continuously controlled by the electrostatic metallic gate, both of which are explained in the LB formula. Moreover, coherence is found to survive at higher temperature in the non-local setup than in the conventional one, while $\tau_\phi \propto T^{-1}$ holds for both setups. This is not inconsistent with the LB formula, but suggests that coherence can depend on how we measure. Such possibility has been overlooked to date, and we believe that this result will shed light on the mechanism of quantum decoherence.

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